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ENGINEERING REPORT

FAA CONTRACT NO. DTFA03-02-C-00044
PHASE 2, CLIN 0002b

Test Plan Analysis

Distribution
General Manager, Enabling Technologies, Dept. 572
Liston Broughton, Technical Sales and Marketing - 4 copies
(Contract Deliverables to be forwarded to:
- Phyliss Schlegel
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- Robert Eastin
- Brent Bandley)

David Steadman
Principal Engineer
Enabling Technologies

David Piotrowski
Senior Engineer
Enabling Technologies

Aubrey Carter
General Manager
Enabling Technologies

Revision B: Revised Nondestructive Inspections, qualifications, equipment and training.

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List of Common Acronyms

CLIN	Contract Line Item Number
DVI	Detailed Visual Inspection
FASTER	Full-Scale Aircraft Structural Test Evaluation and Research Facility
FEA	Finite Element Analysis
FS	Fuselage Station (Aircraft Coordinate System)
GVI	General Visual Inspection
HFEC	High-Frequency Eddy Current
MED	Multiple Element Damage
MOI	Magneto-Optical Imaging
MSD	Multiple Site Damage
MWM	Meandering Wire Magnetometer (Emerging NDI Technology)
NDI	Non-Destructive Inspection
NDTM	Non-Destructive Testing Manual
NFOV	Narrow Field of View Camera, Remote Control Crack Monitoring System
SB	Service Bulletin
SEM	Scanning Electron Microscopy
SIF	Stress Intensity Factor
WFD	Widespread Fatigue Damage
WFOV	Wide Field of View Camera, Remote Control Crack Monitoring System
WL	Water Line (Aircraft Coordinate System)
WS	Wing Station (Aircraft Coordinate System)

EXECUTIVE SUMMARY

This report supports Task 8 of FAA Contract DTFA03-02-C-00044, Development of Test Plan.

The Statement of Work requires that the Final Test Plan contain all of the information required to assure successful test results. This Test Plan Analysis summarizes the analysis that forms the technical basis for the Test Plans to all four panels.

This Test Plan Analysis satisfies the deliverable requirements CLIN 0002b.

CHAPTER 1. INTRODUCTION AND SUMMARY

This report supports Task 8 of FAA Contract DTFA03-02-C-00044, Development of Test Plan.

The Statement of Work requires that the Final Test Plan contain all of the information required to assure successful test results, including:

- Overall technical approaches
- Scope and objectives of each major task area
- Test operating pressure, hoop, axial, and frame loads and frequency
- Visual inspection and NDI requirements
- Test schedule with Gantt chart showing all tasks and milestones
- Pre-test predictions with anticipated number of cycles
- Strain gauge layout and specifications
- Engineering drawings of the test panels
- Data collection requirements
- Responsibilities of each participating organization

This Test Plan Analysis summarizes the analysis that forms the technical basis for the Test Plans for all four test panels. This Test Plan Analysis satisfies the deliverable requirements for CLIN 0002b.

CHAPTER 2. OVERALL TECHNICAL APPROACH

Test Objectives

The broad objectives of the FASTER testing listed in the contractual Statement of Work are:

- Propagate and extrapolate the state of damage beyond one DSG;
- Characterize and document the state of damage through real time NDI, high magnification visual measurements, and post-test evaluation of fracture surfaces;
- correlate analysis methods to determine crack initiation and detection, first link-up and residual strength.

In general, the purpose of the FASTER testing is to provide crack growth, NDI detection, and residual strength empirical data in a controlled environment in support of these broad objectives. Towards that end, the following objectives have been prescribed to the FASTER testing:

1) Advance the state of damage from its current state at one DSG consistent with service damage propagation
   a) The damage of the most interest is the MSD expected to occur in the S-4L lap joint lower skin, lower row. However, MSD/MED damage propagation in any of the WFD susceptible structures is important to this objective. Therefore, damage propagation in the frames, stringers, and outer skin must also be considered.
   b) This objective requires that stress state in the test panel match that seen in service as much as practical within the limits of the FASTER facility. The load spectrum to be applied during the test has been developed using finite element analysis (FEA) and crack growth simulation to produce equivalent MSD crack propagation to an aircraft in service.
2) Document the state of damage throughout the test.
   a) Documentation is required to maintain real-time awareness of the current state of damage, and to provide empirical crack growth data to validate future analyses. Therefore, the test will be paused at designated intervals to conduct the required inspections.

b) In addition, documentation allows an opportunity to evaluate standard and emerging NDI techniques on genuine propagating cracks.

3) Demonstrate the state of damage at which regulatory residual strength requirements are no longer satisfied.

a) This objective is to provide empirical data needed to validate analysis methods at and beyond first MSD link-up.

b) To maximize the data collected, cyclic loading will continue after MSD link-up towards full panel failure for as long as practical, within FASTER mechanical limits.

Test Phases

The test will be conducted in three phases.

Phase 1 runs from the beginning of the test until crack length can be reliably measured, either with NDI or enhanced visual. The crack initiation and growth during Phase 1 will be representative of service, but all rate measurements will be based on striation counts after teardown. NDI will be used to detect MSD as early as possible during the test. The applied load spectrum will include under-load marker bands to assist in the striation counts.

Phase 2 runs from initial crack measurement until a predefined stop criteria is reached. This phase is also run under fatigue loads, with the stop criteria designed to stop damage propagation before the final damage scenario is reached. The primary objective of this phase is documentation of crack growth distribution and rates under fatigue loads, so visual and NDI inspection will be more frequent than during Phase 1. Since undetected small cracks will also be present, under-load marker bands will still be included in the load spectrum.

The primary objective of Phase 3 is to determine the size and state of damage at which the residual strength requirements of 14 CFR 25.571 and JAR 25.571 can no longer be met. The applied test load will be increased so that the critical condition is applied at every cycle. The damage configuration just prior to failure should reflect a valid final damage scenario for service aircraft. The crack growth rates measured during Phase 3 will not be representative of service growth rates, but the data from link-up to panel failure can still be used to validate analytical models. A marker band will separate Phases 2 and 3, but no marker cycles will be included in Phase 3.

CHAPTER 3: DISCUSSION OF TEST PROCEDURES

Strain Gages

The FASTER data acquisition system allows for 64 data channels from all sensors, including strain gages, displacement transducers, secondary load cells, and pressure sensors[1]. Previous tests for lap joint MSD described in reference 1 used 52 channels for strain gage acquisition.

The gauge layouts for all panels are similar to the layout for lap joint cracks documented in Ref [1], with the following differences:

1) The percentage of load carried by the skin in B727 crown panels is higher than in panels similar to Ref [1]. Therefore, the focus for strain gage placement is the lower skin, not the frames and stringers.

2) The critical area for MSD in Ref [1] is the upper skin, so most skin rosettes were installed there. The critical MSD location for these panels is the lower skin, so the focus for strain gage installation is the lower skin just below the lap joint.

3) The crack location in Ref [1] was known in advance. These panels were taken from service with naturally induced MSD, so the crack location is not precisely known and strain measurements must be spread out over the entire primary test area.

4) There was not a circumferential splice in the center of the Ref [1] lap joint panels. Although the lap joint is considered more critical for this testing, several strain gages are installed in the FS 680 circumferential splice on FT2. No gages are placed on the circumferential splices in FT3 and FT4.

In summary, the goals of the strain gage placement are:

1) Determine the strain state in the lower skin along the lap joint, and measure variances in in-plane and bending strains due to skin bulging, MSD crack propagation, and fastener eccentricity.

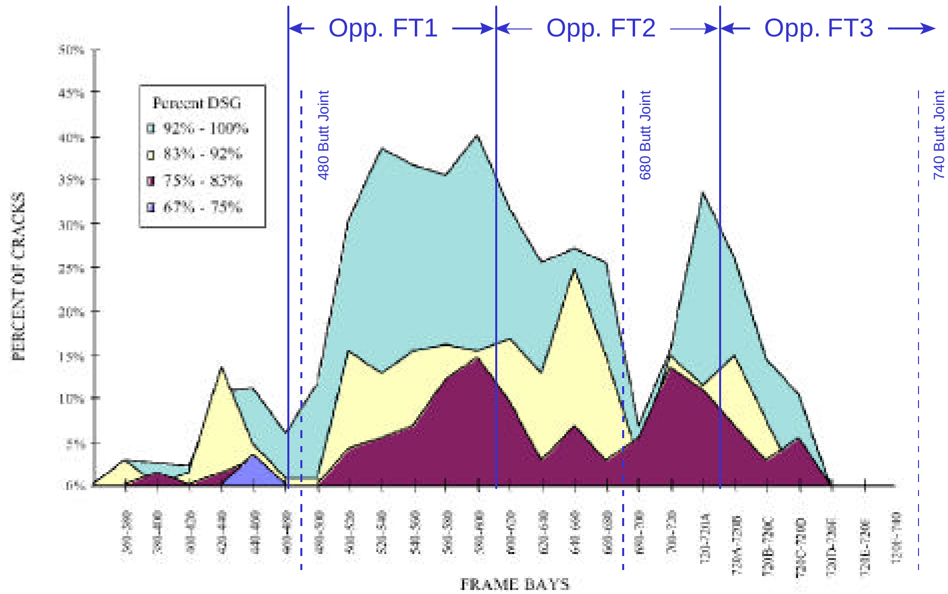
2) Determine how load is transferred from the lower skin across the lap joint.

3) Verify that frame, skin, and stringer strains at the center of the panel are consistent with the applied loads and boundary conditions.

4) If cracking at the FS 680 circumferential joint is detected, measure strains as necessary to determine how load is transferred across the joint.

The strain gage placement is based in part on an analysis of MSD activity shown in Figure 1. This figure establishes the activity color code used in the panel gage drawings in Figure 2 through Figure 5 . These gauge placements use 61 of the 64 allowable data channels. The complete installation drawings have been issued as separate Delta drawings.

To maximize data collection in the S-4 lap joint, strain gages in the FS 680 circumferential joint will be installed but not be allocated a data channel. If circumferential joint cracking is detected, a data channel will be re-allocated from another area that has not demonstrated crack initiation.



Very Active

- FS 500 - 660
- FS 700 - 720B

Active

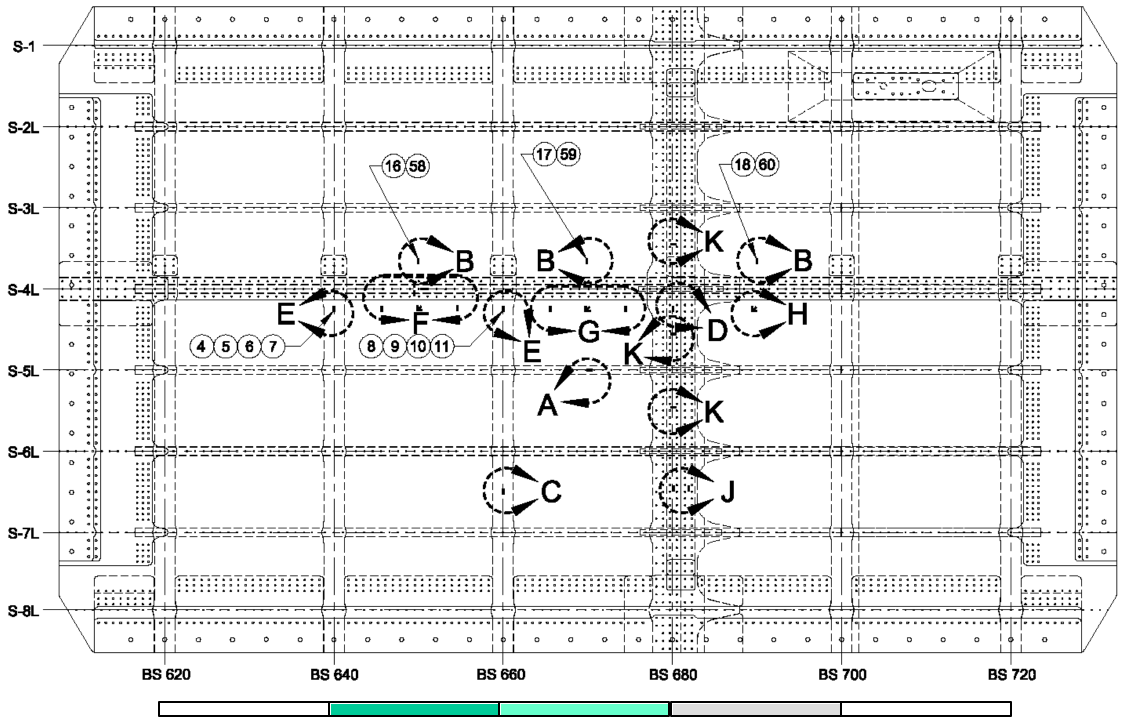
- FS 420 - 460
- FS 660 - 680
- FS 720B - 720D

Less Active

- FS 360 - 420*
- FS 460 - 500
- FS 680 - 700
- FS 720D - 740

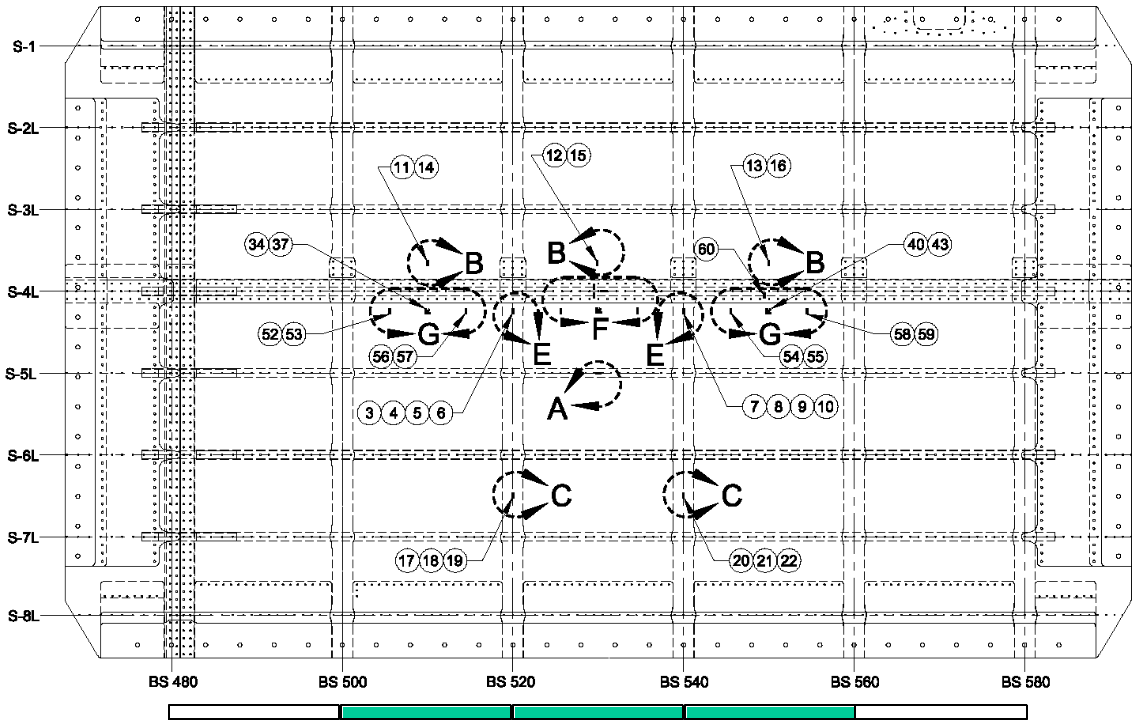
Figure 7: Percent of Holes Cracked, by Percent DSG
(Composite Inspection Data from 105 Airplanes)

Figure 1: Service Lap Joint Data from Ref [2]



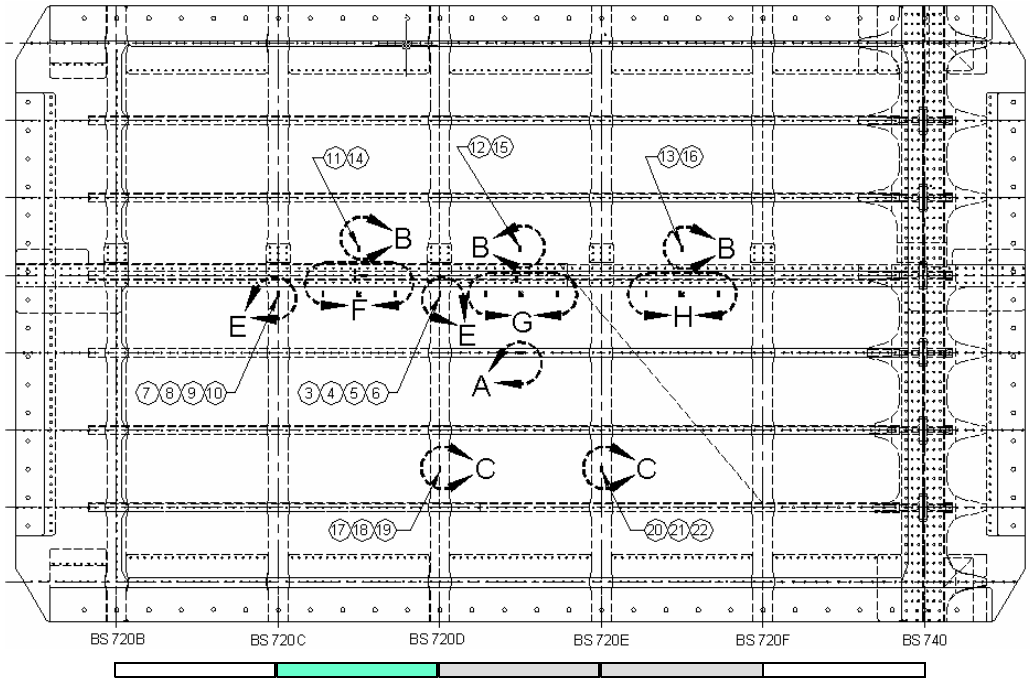
1) Most active frame bay (FS 640 - FS 660)
   a) Lower skin inner/outer rosettes at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4 bay
   c) Inner/outer hoop gages in the fastener pattern above the lower row
   d) Upper skin inner/outer hoop at center bay
   e) Longitudinal axial gages on stringer center and flanges
2) Second active frame bay (FS 660 - FS 680)
   a) Lower skin inner/outer rosette at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4
   c) Upper skin inner/outer hoop at center bay
3) Least active frame bay (FS 680 - FS 700)
   a) Inner/outer rosette at lower skin center bay
   b) Upper skin inner/outer hoop at center bay
4) Hoop axial gages on skin, tearstrap, and frame chords (FS 640 and FS 660)
5) Longitudinal axial gages at outer skin above S-5
6) Longitudinal axial gages at fwd outer skin and splice, FS 680 butt splice (if butt splice MSD is detected)

Figure 2: FT2 Strain Gage Layout



1) Most active frame bay (FS 520 - FS 540)
   a) Lower skin inner/outer rosettes at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4 bay
   c) Inner/outer hoop gages in the fastener pattern above the lower row
   d) Upper skin inner/outer hoop at center bay
   e) Longitudinal axial gages on stringer center and flanges
2) Second active frame bays (FS 500 - FS 520, FS 540 - FS 560)
   a) Lower skin inner/outer rosette at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4
   c) Upper skin inner/outer hoop at center bay
3) Hoop axial gages on skin, tearstrap, and frame chords (FS 520 and FS 540)
4) Longitudinal axial gages at outer skin above S-5

Figure 3: FT1 Strain Gage Layout

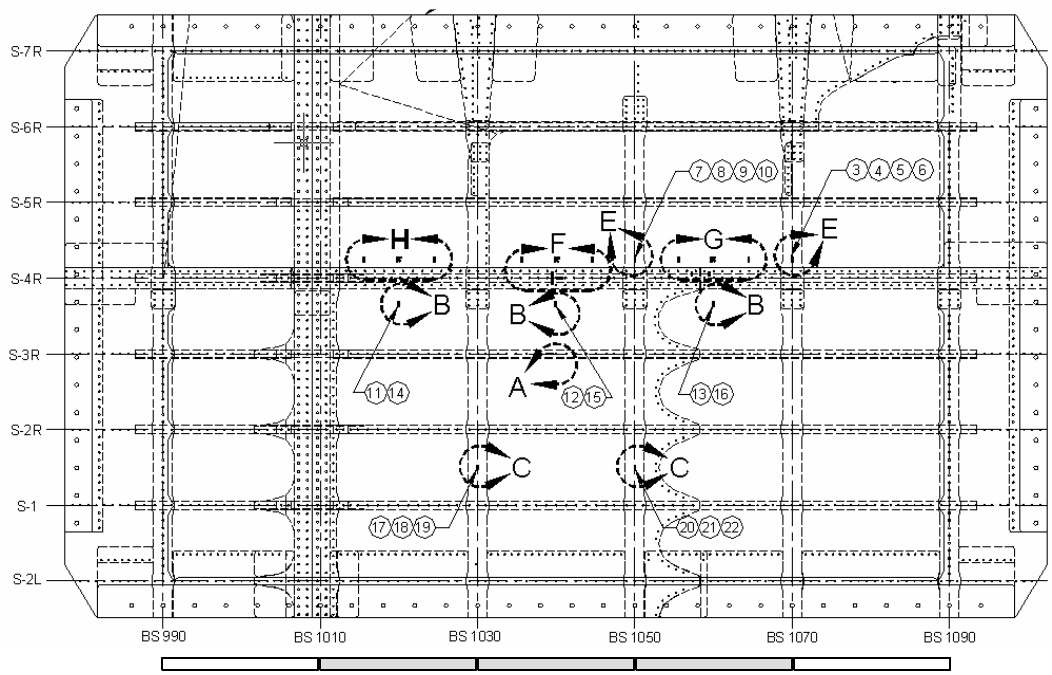


1) Most active frame bay (FS 720C - FS 720D)
   a) Lower skin inner/outer rosettes at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4 bay
   c) Inner/outer hoop gages in the fastener pattern above the lower row
   d) Upper skin inner/outer hoop at center bay
   e) Longitudinal axial gages on stringer center and flanges
   f) Hoop axial gages on skin, tearstrap, and frame chords
2) Second active frame bays (FS 720D - FS 720F)
   a) Lower skin inner/outer rosette at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4
   c) Upper skin inner/outer hoop at center bay
3) Longitudinal axial gages at outer skin above S-5

Notes:

- Skin tapers thicker towards FS 740
- Heavy frame at FS 740 (at the wing front spar buckhead)

Figure 4: FT3 Strain Gage Layout



1) Most active frame bay (FS 1050 - FS 1070)
   a) Lower skin inner/outer rosettes at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4 bay
   c) Upper skin inner/outer hoop at center bay
   d) Hoop axial gages on skin, tearstrap, and frame chords
2) Second active frame bay (FS 1030 - FS 1050)
   a) Lower skin inner/outer rosette at center bay
   b) Lower skin inner/outer hoop gages at 1/4 and 3/4
   c) Upper skin inner/outer hoop at center bay
   d) Inner/outer hoop gages in the fastener pattern above the lower row
3) Longitudinal axial gages at outer skin above S-5

Notes:

- FT4 has shown less service cracking than the forward fuselage
- Door surround structure, FS 1010 joint, and the upper skin bonded doubler may affect strain results
- MSD is most expected is in the aft bay, with 5/32 fasteners
- The stress gradient at the bonded doubler runout is not ideal for strain gauges, so inter-fastener gauges are placed in the center bay

Figure 5: FT4 Strain Gage Layout

Underload Marker Bands

A marker bands sequence is included in Phase 1 and Phase 2 to improve the precision of the crack growth history reconstruction. Implementation of an underload marker band is required by the project Statement of Work, but no other details are specified.

The marker sequence chosen is the 6-4-10 Sequence shown in Figure 6. The figure shows that one of three bands occurs every 1,000 cycles. The band is created through 100 cycle valleys of 75% magnitude, separated by 10 cycles of 100% magnitude. The identifier 6-4-10 refers to the number of distinct valleys within one band.

This sequence was used successfully in the full-scale fatigue tests and fractography of Al 2024-T3 in Ref [3], with good striation visibility reported. In addition, this sequence was implemented successfully in previous FASTER tests[4] with no reported difficulties.

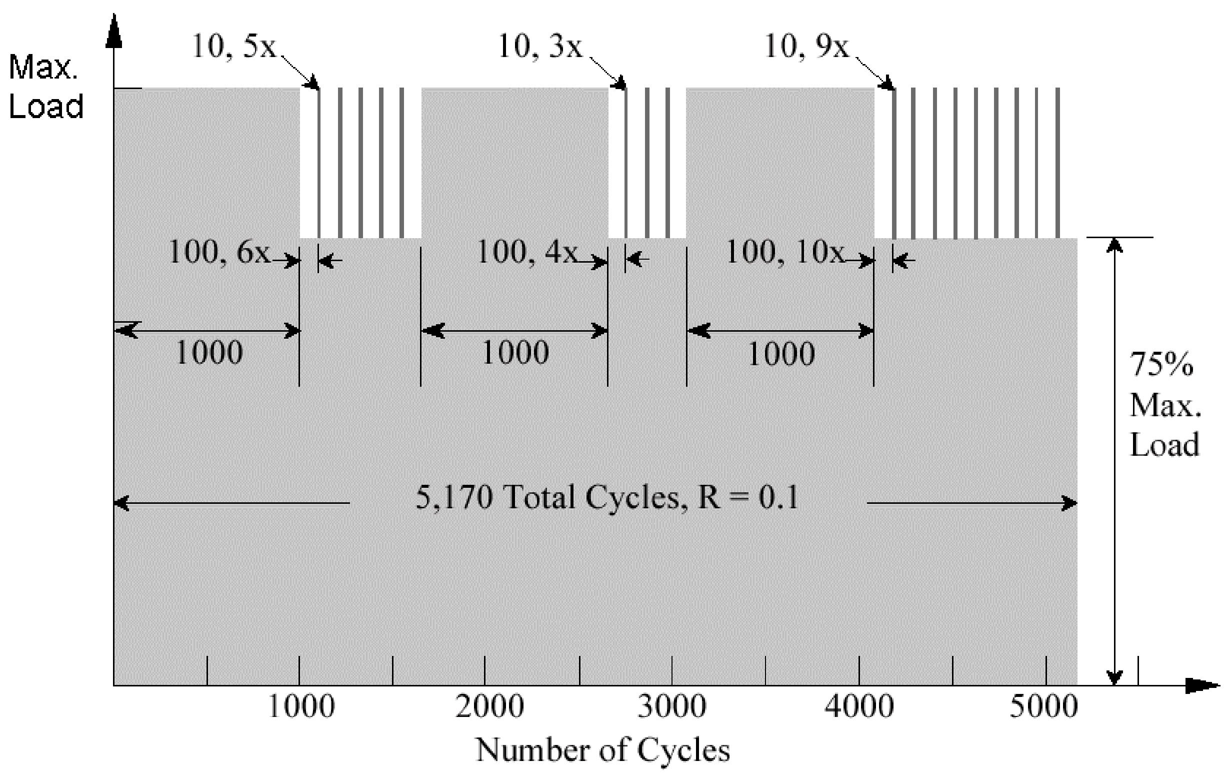


Figure 6: 6-4-10 Underload Marker Band Sequence

Non-Destructive Inspections

There are several “Standard NDI” inspections (i.e., MFEC and HFEC) which will be conducted initially every 2500 cycles, or at each internal access opportunity. These inspections will be conducted by FAA-TC personnel initially, but taken over by Delta certified and qualified inspectors after 10,000 pressurization cycles during the first test. This is due to the critical nature of determining the initial detectability point. Future Test Plans could be changed, if the FAA Technical Center inspectors are shown to be “qualified” to perform a greater share of the inspections in future tests.

There are several "Emerging NDT" Techniques which will be used to inspect the panels at 5,000 cycle intervals after an initial inspection at 10,000 total cycles. MOI, Turbo-MOI, MWM, Rivet Check and GMR are emerging technologies which were selected from evaluations of the Pre-Teardown Inspections for use during FASTER testing. These technologies generally provide better detectability than the current AD mandated LFEC sliding probe inspection.

Delta will maintain responsibility for the NDT and will periodically assess the state of the inspections. This will include on-site assistance and advisement during the first Standard NDT Inspections. Additional or fewer visits may be taken depending upon the state of the inspections, including the comfort level of the FAA-TC inspectors. After 10,000 cycles, Delta will take over the Standard NDT Inspections from FAA-TC, at least for the first test panel (FT2).

Typical Industry Inspector Qualifications

Several Emerging NDT technologies will be examined during the program. Due to the unique nature of these technologies, generally only "Qualified and Certified" inspectors should conduct these "Emerging NDT" inspections. At a minimum, the inspector should be a Level II in Eddy Current, with a Level III in Eddy Current is recommended. Generally, a Level I inspector can only perform inspections in the Boeing NDT manuals or a Level III approved written procedure, but guidance from a Level II or Level III is recommended. The Emerging NDT Inspections generally require a Level II or III to perform the inspection to a satisfactory confidence level since adequate inspection procedures have not been established for a Level I to follow.

Level I-Special is the lowest certifiable Level of an inspector. Level I Special is only a specific certification, with inspectors only allowed to conduct the exact inspection for which they are trained.

However, industry standard documents, such as ASNT-TC-1A, CP-189, ATA 105, NAS 410, and MIL-STD-410, all contain requirements of at least 40 hours of classroom time followed by 210 OJT hours in that specific inspection. To be certified to perform both the internal MFEC and external LFEC sliding probe inspections, each individual would be required to have a 40 hour training course and 420 hours of OJT. Certification to a Level I would require even more hours of OJT, while a Level II certification would require additional OJT and classroom hours beyond Level I certification. Additionally, the FAA has performed previous studies which have shown that recency of experience, recency of training, and level of experience and training all have a significant impact of the detectability.

Training Course

Delta taught an accelerated training course along with assistance from FAA-AANC to the FAA-TC inspectors in January 2004. It is estimated that approximately six weeks of training were taught in four days consisting of standard NDT, MOI, RivetCheck, and Jentek MWM. Even though overwhelming, the FAA Technical Center inspectors performed very well, mastering the techniques to the satisfaction of the instructors. Capabilities were demonstrated on all techniques both in the classroom table-top arrangement as well as on the FASTER rig.

On January 26-28, 2004, Jentek delivered the MWM and provided a training course. Training and official delivery was arranged to coincide as close to the test start-date as possible. After initial set-up, the MWM inspection was performed on the panel in the FASTER rig. Concerns about some strain gauge positioning possibly interfering with the trolley footprint were alleviated as the inspection was performed satisfactorily. Since FT2 was not examined by Jentek in Atlanta during the evaluation of Emerging NDT Techniques in June due to contractual requirements (already in shop for modification), this also served as the initial baseline. No indications were noted during these scans.

Classroom training for MWM entailed an overview of the MWM technology and how it differs from conventional eddy current, along with discussions on how to maneuver through the software and how to scan and process images. All steps were followed by everyone in the room as the image from the computer was projected onto the screen. Next, a demonstration on how to perform the scans was performed, using a piece of cracked lap joint from Boeing. The remainder of the MWM training session was dedicated to practical training with FAA Technical Center inspectors separated into teams of two. One team went to perform training on the FASTER rig, while the other team concentrated on the table-top classroom instruction.

On January 29, MOI and Rivetcheck were taught by AANC at Sandia after a rapid session on Eddy Current Basics and Theory. Delta's Level II refresher course was used during the instruction, effectively compressing a 40 hour course into two hours. Notebooks were provided for each participant with all powerpoint slides, procedures, tips, and datasheets. MOI and RivetCheck were taught for the balance of the day, with both table-top classroom instruction and FASTER rig location used per Boeing 727 NDT Manual, Part 6, Chapter 51-00-00, Figure 19 and 25, respectively. Practical examples in the form of Delta's lap splice panels were used during the training as well as the applicable reference standards. Each procedure was demonstrated by following the Boeing 727 NDT Manual procedure line by line.

On the final day of training, the LFEC sliding probe, internal MFEC, and internal HFEC procedures were taught. The LFEC sliding probe procedure (Boeing 727 NDT Manual, Part 6, Chapter 53-30-27, Figure 13) was connected to National Instruments' acquisition software through the NDT-19 instrument which will record the scan. The data can then be exported to Excel for further analysis. Training was performed on the specifics of this operation.

The internal HFEC and internal MFEC inspections were taught per the Boeing 727 NDT Manual, Part 6, Chapter 51-00-00, Figure 23 and Chapter 53-30-27, Figure 17 using the Hocking Phasec 2200 instrument. Each of these procedures will use the screen freeze command to save the images, but will not provide the same detail of information as the National Instruments' software. The internal HFEC and MFEC inspections are not conducive to the same data acquisition due to frequent use of liftoff. Some electrical noise, believed to be from the probes, prevented full teaching of the internal MFEC at this time. Several practical examples were used to demonstrate the procedures including two universal links from L1011 landing gear. The examples, used during Delta's NDT Training classes, showed a good example of two cracks in a radius which could not be seen with the naked eye, but were readily detected with HFEC. Lastly, the internal HFEC was performed in the FASTER rig to examine for cracking in the stringer clips, frame-to-stringer attachments, and stringer-to-frame attachments. Each FAA Technical Center inspector performed the internal HFEC with little difficulty.

POD Plans – Qualified Inspectors

It is important to point out that these inspectors will not be "certified and qualified" to any Level, including Level I -Special, and the POD of the inspections conducted with uncertified inspectors may be worse than a "certified and qualified" inspector with recent experience and training. For this reason Delta inspectors will take over the Standard NDT Inspections after 10,000 cycles of the first test.

However, since the FAA Technical Center inspectors performed well during the training course, it was decided to collect data of all the techniques taught. The collection of data will result in Probability of Detection (POD) results of the FAA personnel, which will then be compared to industry averages. The POD for the inspectors is predicted to match industry averages.

Delta's lap splice panels were left at the FAA Technical Center for practice and to accumulate data for POD curves. It is anticipated that the POD data gathered will show that the FAA Technical Center inspectors are just as "qualified" as an industry inspector, even without the "certification". This will lead to increase use of the FAA Technical Center inspectors, and conversely a decreased dependence on AANC and Delta inspectors, on future tests. However, due to the time lapse between instruction and actual inspection, Delta will send at least one representative during the first Standard NDT inspections at 2500 cycles of the first test and both Delta and Sandia representatives will be present during the initial Emerging NDT techniques at 10,000 cycles of the first test. Additional on-site assistance could occur, if requested or deemed needed.

Information was gathered on the MWM, MOI, RivetCheck, internal MFEC, and external LFEC using the same panels. All of these methods were previously performed during the Pre-Teardown inspections in Atlanta, but with different inspectors. Therefore, this data could also show a difference between actual inspectors and inspectors provided by the vendors, or inventors of the technique. All data will eventually be included in the Inspection Capability Reports (Task 11) and may be included in the database.

NDI Equipment

All equipment throughout this program is property of the AANC at Sandia, provided to the FAA Technical Center on long-term loan. Basic eddy current instruments, reference standards and probes necessary for the internal MFEC and internal HFEC inspections were delivered to the FAA-TC from FAA-AANC during the training course. Emerging NDT equipment such as Rivet Check, MWM, and MOI are currently owned by FAA-AANC and were also delivered during the training course. Instead of delivery to AANC at Sandia, the FAA arranged to have the system delivered to the FAA Technical Center, although the system belongs to AANC at Sandia. Additionally, AANC at Sandia provided some National Instruments' acquisition software along with a laptop computer on long term loan to FAA-TC for the duration of the program.

If available, Turbo-MOI and NASA GMR must be borrowed by FAA-AANC. These two inspection techniques will only be performed if the equipment can be provided for an extended period of time, for example a beta test site. Otherwise, the Emerging NDT Inspections will consist of MOI, Jentek MWM, and Rivet Check.

Signal Acquisition Protocol

Generally, the signals or screen representations of interest should be captured electronically for archiving in the database for future comparisons. However, not all scans should be saved for future use. Scans or screens which produce rejectable signals must be recorded. Scan or screens with nonrejectable indications should also be recorded. A nonrejectable indication is a small indication of a flaw, but doesn't quite meet the threshold to be a reject. Additionally, all strange signals should be documented and recorded, but only after a thorough analysis has taken place consisting of confirming all instrument settings and recalibration. Fastener sites with no indications should not be recorded.

Emerging NDI Evaluation

A qualitative evaluation of Emerging NDI techniques through comparison to the Standard NDI techniques was accomplished during the Pre-Teardown inspection, Field Inspection, and actual in-service experience. Four categories were created for comparison:

- Sensitivity: based on the number of inspection findings, both rejectable and recordable, and then correlated with the internal MFEC inspection indications. No POD or false call data is available.
- Ease-of-use category: calibration and use of the software required for an actual NDT inspector to interpret the results.
- Speed of the inspection: includes the initial scanning rate and the final data analysis, if separate from the inspection
- "Fieldability": portability of the inspection, as well as the projected durability to operate in the airline hangar environment (i.e., wires, connections, "drop-ability", etc.). Also includes FASTER shear fixture clearance.

Each NDI technology was rated in each category on a scale from 1-5

5 = Substantially Above Current Inspections
4 = Above Current Inspections
3 = Neutral/Same as Current Inspections
2 = Below Current Inspections
1 = Substantially Below Current Inspections

The evaluation score is calculated by summing the ratings for each category, with the Sensitivity rating counted twice. The maximum evaluation score is 25 points. The results are in

Table 1, which shows Turbo MOI/MOI, Self-Nulling Rotating Eddy Current I (Rivet Check)and II (GMR), and Eddy Current Array Sensor (MWM) as the technologies selected.

Table 1: Results of Emerging NDI Technology Evaluation

Key:

5 = Substantially Above Current Inspections

4 = Above Current Inspections

3 = Neutral/Same

2 = Below Current Inspections

1 = Substantially Below Current Inspections

Max. Total = 25 points

NOTE: Sensitivity counts twice

Technique/ Vendor	Sensitivity (MAX=10)	Speed (MAX=5)	Ease-of-use (MAX=5)	Fieldability (MAX=5)	**Total (MAX=25)**
Turbo Magneto Optical Imaging	8	4	4	5	**21**
Self-nulling Rotating Eddy Current Probe I	10	2	3	4	**19**
Self-nulling Rotating Eddy Current Probe II	10	2	3	4	**19**
Magneto Optical Imaging	6	4	4	5	**19**
Time-varying Eddy Current Array Sensor	10	1	1	2	**14**
Pulsed Eddy Current	8	2	2	2	**14**
Array Eddy Current	6	2	3	3	**14**
Eddy Current Rotating C-scan	8	1	2	2	**13**
Thru-Transmission Eddy Current	8	1	3	1	**13**
Eddy Current C-scan I	8	2	2	1	**13**
Eddy Current C-scan II	6	2	2	3	**13**
Rotating Eddy Current Probe III	6	3	2	2	**13**
Ultrasonic System	4	1	2	3	**10**
Digital Radiography	6	1	1	1	**9**
Acoustically Excited Laser Vibrometry	2	1	1	1	**5**

CHAPTER 4: PRE-DEFINED TEST MILESTONES

Within each test Phase, two types of milestones are defined

Hold Point: Hold Points during the test are opportunities to revise the test objectives and procedures based on the panel's performance to that point. Once the Hold Point is reached, testing will stop until the Delta and FAA consensus is that the test should continue. A revision to this Test Plan may be required.

End of Phase Criterion: This criterion defines when the specific test phase is completed and the next phase should begin. If more than one criterion is listed, then the phase ends at whichever condition occurs earlier.

Phase 1

End of Phase Criteria

This phase ends when an MSD/MED crack can be measured visually with the Underwater Remote Camera or three consecutive holes with MFEC indications, whichever occurs earlier.

This criteria indicates that a MSD/MED condition has evolved to the point where accelerated inspection intervals are justified. It is expected that MSD will first be evident through multiple MFEC indications as demonstrated on S-4R during the Pre-Teardown Inspection. However, the "measured visually" criterion ensures that available data is collected even if the panel develops a lead crack in an otherwise sparse MSD array.

Phase 2

Hold Point

Hold the test when two adjacent holes have cracks growing towards each other that can be measured with the Underwater Remote Camera.

The End of Phase below is based on an assumed distribution of MSD: that the cracks toward the center of the bay are significantly larger than those near the frames and tearstraps. This assumption represents a more sparse MSD array than the classical TOGAA scenario of equal length diametric cracks at every hole.

A dense MSD array like the TOGAA scenario can fail through ligament yielding at crack lengths less than 0.3”. If the test panel develops a dense MSD array, then the End of Phase Criteria must be revised. The sparseness of the evolving MSD array will be evaluated at this Hold Point.

End of Phase Criteria

The transition to the increased loads of Phase 3 will be done at the end of any of the three marker blocks. To prevent overshoot of a 1” total length, Phase 2 ends after the first marker block following 0.9” maximum total length or the first MSD link-up, whichever occurs earlier.

This criteria is based on the 1” tip-to-tip condition as an established conservative estimate of the point where MSD causes degradation below the aircraft’s required residual strength. The results of the MSD propagation simulation show 2,000-2,500 cycles from 0.9” to 1”, and 500 - 1,000 cycles from 1” to unstable MSD link-up.

Phase 2 ends after a marker cycle to ensure that the point where the applied test loads are increased is clearly evident on the fracture surfaces. No marker bands are applied during Phase 3.

Phase 3

Hold Point

Hold the test when one tip of a large lead crack reaches a tearstrap.

It is expected that this point is very close to the end of the test. If flapping occurs, it constitutes an obvious partial failure and the test is practically concluded. However, if the tearstraps arrest the lead crack but flapping does not occur, the test will continue as long as pressure can be maintained. This hold point provides an opportunity for Delta /FAA discussion during the last stage of the test.

End of Phase Criteria

The load spectrum should be continued until pressurization can no longer be maintained, propagating the MSD damage as much as possible to global panel failure. It is acceptable to end the test anytime after the damage to the panel is obvious to an external cursory view (i.e., a walk-around inspection)

The intent is to continue the fatigue testing for as long after MSD link-up as practical. Typically, pressurization will not be possible after an obvious partial failure.

CHAPTER 5: TEST SPECTRUM DEVELOPMENT

Analysis Hierarchy

Determination of the appropriate test spectrum required a series of finite element modeling and crack growth analysis. The object of the analyses was to determine the required stress state in the test panel lap joint that produces equivalent MSD crack growth to that seen in service. A flow chart of FEA hierarchy is shown in Figure 7.

The technical details of these analyses are discussed fully in the Data Analysis Report (4-087051-20). In summary, the analysis sequence is as follows:

1) For the forward fuselage, use Global Stiffness Model to determine load distribution. The Global Stiffness Model Shell is 420" long, from FS 440 to FS 740. The fuselage pressure boundary is represented with shell elements. The fuselage frames, stringers, frame-stringer clips, intercostals, and cargo door sills are represented with offset beam elements.

2) Use Intermediate Stiffness Model to determine the stress state in the test panel area. In this model, the fuselage skin, frames, and stringers are represented by shell elements.

3) Find the test spectrum

    a) Use the Crack Growth Equivalency Analysis to determine a simple test spectrum that produces MSD growth equivalent to the complex service spectrum. The Equivalency Analysis assumes an infinite array of diametric crack holes, and includes cycle-by-cycle analyses for three potential test spectra compared to a baseline service spectrum. The Equivalency Analysis has two components; circumferential crack equivalency is used to determine an equivalent load factor, while longitudinal crack equivalency is used to determine the equivalent pressure factor.

    b) Iterate the applied loads on the Test Panel Stiffness Model so that stress state at S-4 under the test spectrum is equivalent that in the Intermediate Stiffness Model during the service spectrum. The Test Panel Model is similar to the Intermediate Model except it has load points and kinematic boundary conditions that represent the FASTER fixture.

4) Predict the test results

   a) Use Half Bay Shell Model to find detailed stress distribution throughout the S-4 joint. This FEA model is a detailed representation of S-4 that includes three circumferential bays and one half of a longitudinal bay, with all major structural details modeled as shells. The fasteners in S-4 were individually modeled as cylindrical shells that connect the upper skin to the lower skin or the stringer to the lower skin. This model contains more than 100,000 degrees of freedom.

   b) Use the stress state results from the Half Bay Shell Model in the MSD Propagation Simulation to make pre-test predictions of test duration and residual strength. This LEFM simulation uses established stress intensity factors and growth rate equations to forecast test performance within upper and lower bounds.

Test Spectra

For the forward fuselage (FT1 – FT3), the fatigue spectrum during Phase 1 and Phase 2 will be Constant Amplitude of (ΔP+0.3) psi +1.25g, with stress ratio at 0.1. For FT4, an additional component based on 10% limit fin gust is added. These spectra were based on the following considerations:

- The normal operating pressure ΔP for the 727 is 8.6 psi. The 0.3 psi increase in cabin pressure is included in the test spectrum to balance the crack growth rate in response to the 0.1 stress ratio.
- Characterization of the fracture surfaces has not revealed evidence of significant variable-amplitude effects.
- Any spectra other than constant amplitude introduces significant complexity to the conduct of the FASTER tests and to the subsequent validation of analysis methods using the test results.

Assuming lap splice MSD is the dominant damage type at the end of Phase 2, the residual strength spectrum during Phase 3 will be Constant Amplitude 1.15*(ΔP + 0.3 psi aero) +1.0g condition, with a 0.1 stress ratio.

Actuator Loads

The total loads to be applied on the hoop and longitudinal edges are outlined in the Data Analysis report. Load at each actuator is determined by dividing the total edge load by the number of actuators per side. The FASTER facility provides 6 frame, 7 skin hoop and 4 skin axial load control points, so dividing the total load evenly among the actuators leads to the values for the fatigue and limit load test conditions contained in the individual test plans.

CHAPTER 6: PRE-TEST PREDICTIONS

Uncertainty in the test panels' current damage state necessitates that a bounding approach be used for pre-test predictions. Analysis supporting this prediction uses LEFM methods with established ΔK and growth rate solutions, with stresses from geometrically non-linear FEA. The simulation methodology is discussed in detail in the Data Analysis report.

This pre-test prediction was initially developed for the FT2 and FT1 test panels, and the results are generally valid for FT3 and FT4 as well. The uncertainty in the test panels' damage state overshadows the other differences between panels, such as FT3's thicker skin gauge. The lap joint geometry is similar between all panels, with hoop stress from pressurization as the dominant fatigue stress. The pre-test predictions may be revised for the later panels based on experience gained during the first FASTER tests.

Phase 1 And Phase 2

During Phase 1 And Phase 2, the test panel is loaded similar to conditions seen in mainline service. The simulation begins with 0.0005" crack on both sides of every hole. This initial flaw size was chosen to be as small as possible, but still produce a ΔK above the growth threshold.

Cracks grow relatively slowly during Phases 1 and 2, so several steps were taken to increase computation efficiency:

- The simulation step size is set to 1000 cycles.
- The interaction β-factor is linearly interpolated from values in $\beta(a_1,a_2)$ table lookup.
- The adjacent crack length a_2 is average value over the simulation step, assuming a constant growth rate.

The predicted Length of Phase 1 depends highly on the assumed initial state. The NDI inspections to date have not provided a definitive damage state, in that there have been no NDI indications to date on any of the panels.

- Internal HFEC of every hole during the during Field Inspection and Pre-Teardown Inspections had a 90% POD at 0.090” (0.050” + 0.040” tail shadow).
- BHEC of lower row in edge bays of each panel during modification had a 90% POD at 0.050”.

The bounds of the pre-test predicts are based on differing assumptions of initial damage state and MSD propagation. The crack growth curves used for these predictions are shown in Figure 8.

1) Lower Bound predictions are based on an infinite array of thru-cracks (TOGAA scenario)
   a) Assumes .090” cracks at center hole at start of Phase 1
   b) Phase 1 ends at first inspection at 2,500 cycles
   c) Phase 2 starts at seconds inspection (assumes cracks were missed during first), ends at yield of infinite series
2) Forecast predictions are based on the crack growth simulation
   a) Assumes .040” cracks at center hole at start of Phase 1
   b) Phase 1 ends at 0.140” center hole, based on estimated Remote Camera Detectability
   c) Phase 2 ends at 1” tip-to-tip
3) Upper Bound predictions are based on a single lead crack
   a) Assumes .015” crack at center hole at start of Phase 1
   b) Phase 1 ends at 0.3”, based on estimated Remote Camera Detectability
   c) Phase 2 ends at 1” hole-to-tip (0.844”)

Phase 1 Duration

Lower Bound - 2,500 cycles

Forecast – 13,000 cycles

Upper Bound - 50,000 cycles

Phase 2 Duration

Lower Bound - 6,000 cycles

Forecast - 17,000 cycles

Upper Bound - 34,000 cycles

FS 680 Butt Joint Analysis

An analysis for MSD growth in the FS 680 butt joint was also conducted. This analysis assumes the TOGAA thru crack scenario, and is compared with the similar lap splice analysis in Figure 9. The conclusion of this conservative analysis is that the FS 680 butt joint is significantly less critical for MSD than the lap joint lower row. However, the critical fasteners in the FS 680 butt joint will still receive NDI inspections during FASTER testing.

Phase 3

During Phase 3, the test loads are increased to be equivalent to a 1.15 ΔP + 1g condition based on the 14 CFR 25.571 and JAR 25.571 requirement. The Phase 3 simulation uses the same simulation tool, except the numerical analysis is tightened to maintain precision with the rapidly growing MSD state:

- The simulation step size is reduced to 100 cycles or less
- The interaction β-factor is calculated explicitly using Simpson's Rule

The simulation continues until the Link-Up Margin of Safety equals zero, where

$$M.S._{LU} = \frac{\sigma_{LU}}{\sigma_{ff}} - 1$$

The link-up stress is determined by Ingram[5] tuned plastic zone touch criteria. At link-up, the crack length is set to the sum of the link-cracks, and the simulation continues. The simulation stops when the SIF of a newly linked crack is greater than K_c, indicating an unstable fracture condition.

The duration of Phase 3 is highly dependent on the assumed crack array. Two Phase 3 simulations were conducted: the continued propagation of the Phase 2 simulation array, and a less conservative simulation with shortened (0.150") cracks opposing the lead crack. The duration predictions are based on plot comparing those two simulations shown in Figure 10:

- Infinite array TOGAA scenario has no Phase 3
- The Lower End prediction is factored down 50% from the Phase 2 array
- The Forecast is factored up 200% from the Phase 2 array
- Upper End prediction is rounded up from shortened opposing cracks array.

For either scenario, Phase 3 ends shortly after the first MSD link-up.

Phase 3 Duration

Lower End - 200 cycles

Forecast - 1,000 cycles

Upper End - 5,000 cycles

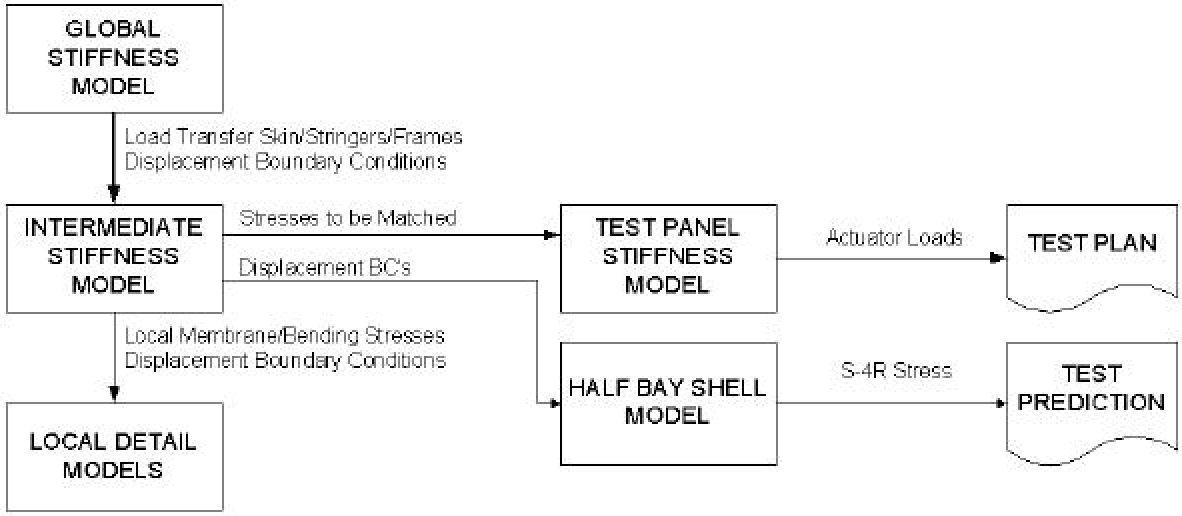


Figure 7: Finite Element Analysis Hierarchy

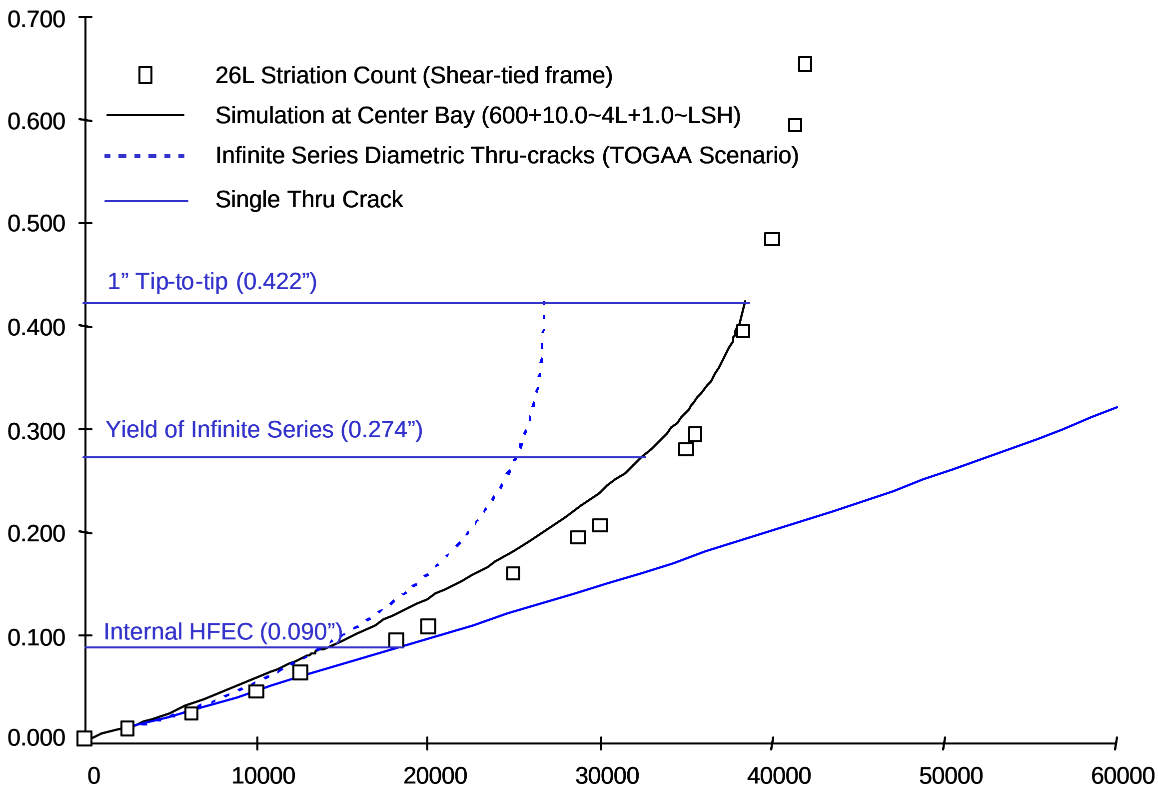


Figure 8: Phase 1 and 2 Crack Growth Curves

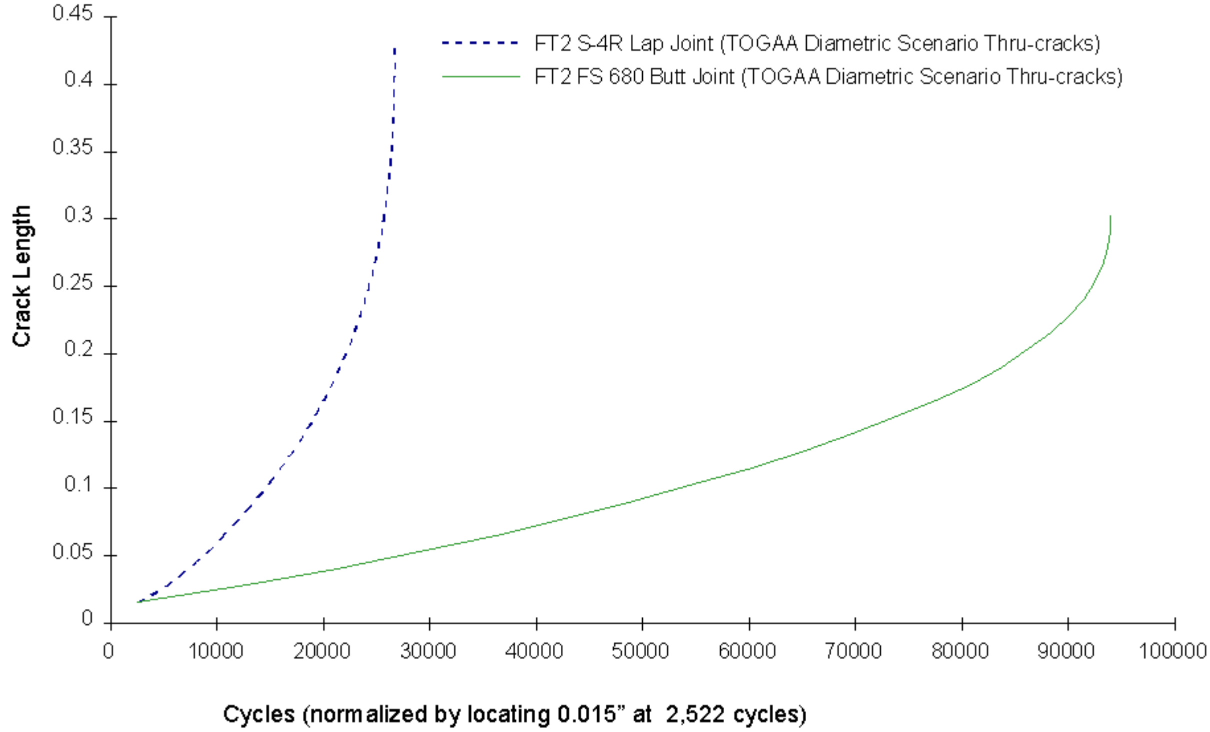


Figure 9: S-4R Lap Joint vs FS 680 Butt Joint Crack Growth Comparison

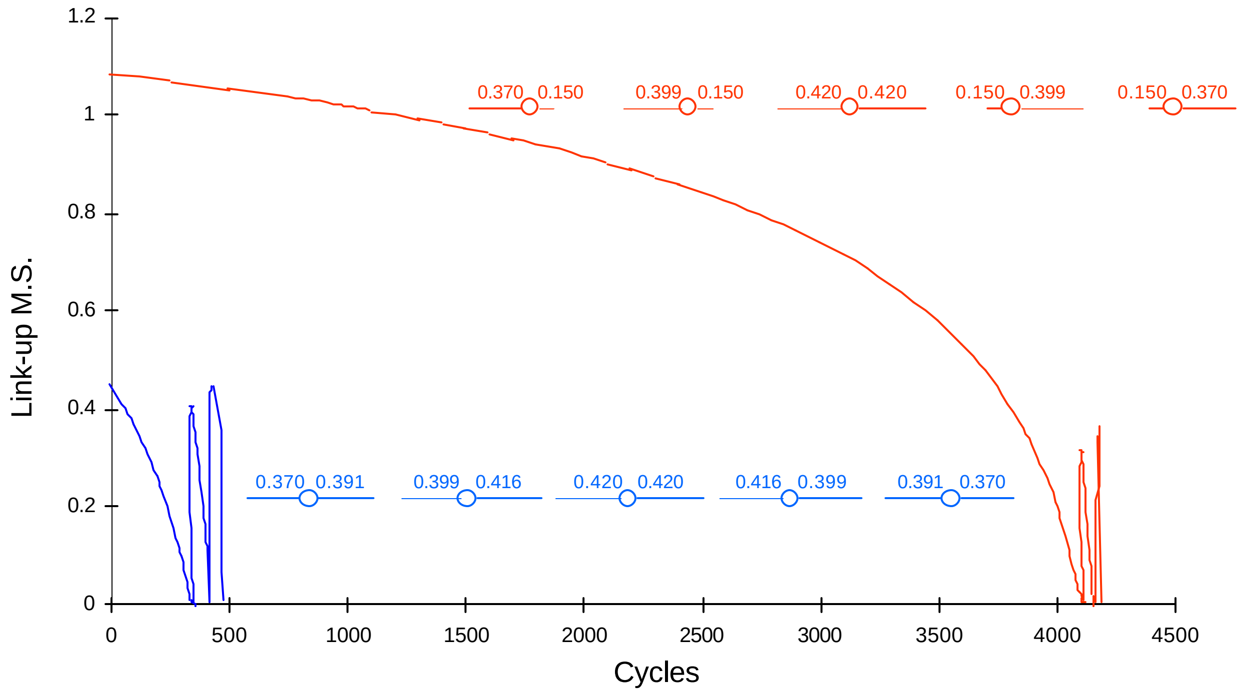


Figure 10: Phase 3 Simulation Results

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